THE TIMING OF REPETITION PRIMING: EX-GAUSSIAN ANALYSIS OF RESPONSE TIMES

Kayleigh J Nemeth

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Approved by:

Peter Gordon

Jennifer Arnold

Kelly Giovanello

ABSTRACT

Kayleigh J Nemeth: The Timing of Repetition Priming: Ex-Gaussian Analysis of Response Times
(Under the direction of Peter Gordon)

One of the simplest forms of priming is repetition, measured as facilitation of target-word recognition by an identity prime. Ex-Gaussian analysis of ocular (Experiment 1) and manual (Experiments 2 and 3) response times to *repeated* and *unprimed* words was employed to examine the nature of such facilitation. Ocular response times revealed an effect of repetition on mu, which represents a modal shift in the normal distribution between conditions (i.e., the priming facilitation is automatic and prospective). In contrast, manual response times revealed an effect of repetition on tau, indicating a systematic divergence of the distributions with more facilitation on slower trials (i.e., the facilitation is retrospective or strategic). Repetition provides both early prospective and later retrospective facilitation to target recognition, yet only ocular response times are sensitive to the early component, highlighting the need for more ocular-response priming studies in a body of literature rich in manual-response studies.

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INTRODUCTION

Repetition priming is a phenomenon whereby a word (e.g., “dog”) is recognized or responded to more quickly when it is preceded by itself (“dog”) than by an unrelated word (e.g., “cup”). The first word is referred to as the prime, and the second word as the target. Historically, repetition priming has been studied in two main ways: short-term priming and long-term priming. In short-term priming studies, the prime is typically displayed for a very short time right before the target is presented; in long-term priming studies, certain words are typically repeated across trials (Scarborough, Cortese, & Scarborough, 1977; Bowers, 2000). Often, short-term primes are masked to ensure that participants do not form conscious episodic memories of them. Short-term priming studies have generally led to the development of automatic prospective models of priming, and long-term priming studies have led to more retrospective accounts.

For example, one task that has been heavily utilized to study repetition priming is the lexical decision task (LDT), in which participants must decide whether a certain item on each trial is a word (e.g., “dog”) or a non-word (e.g., “dod”) (Scarborough, et al., 1977). In a typical short-term repetition-priming LDT experiment, a masked prime appears on the screen for a very brief amount of time (generally less than 80ms) before the target. A typical long-term repetition-priming LDT does not include any masked primes; rather, certain words are presented in more than one trial (i.e., a long-term repetition). The dependent measure in short-term and long-term LDTs is almost always response time to the target in the repeated versus new/non-repeated conditions. These different methodological approaches to studying priming have led to several theories about the mechanisms of priming, including abstractionist and memory-based accounts

(Bowers, 2000; Bodner & Masson, 2001). Abstractionist accounts generally state that repetition primes provide automatic prospective facilitation to target processing, whereas memory-based accounts generally conclude that prime facilitation is retrospective and relies on episodic memory (Forster & Davis, 1984; Evett & Humphreys, 1981; Forster, 1999; Scarborough et al., 1977; Tulving & Schacter, 1990; Tenpenny 1995).

The majority of priming studies use manual response times as a dependent measure, and analyze them with means-based models. The current study uses ex-Gaussian analysis of ocular (Experiment 1) and manual (Experiments 2 & 3) response times to examine the effect(s) of repetition priming. Ocular response times are much faster and more naturalistic than manual response times, and thereby provide a more direct measure of word processing time with less influence of post-lexical processes and button-press response execution (Hoedemaker & Gordon, 2014; 2017). The present experiments help to build connections between studies which utilize manual button-press and oculomotor response times, indicate the important differences in the results, and highlight the need for more oculomotor-response priming studies. In order to properly contextualize the present research, the following sections introduce the theoretical framework for priming and its relation to distributional analysis.

Early Abstractionist/Prospective Models of Repetition Priming

Short-term masked priming LDT studies have documented a quickly-dissipating repetition effect of constant size, which led to the development of *pure abstractionist models* of repetition priming (Tenpenny, 1995). Abstractionist models state that repetition priming is facilitation of target processing by consecutive access to the same orthographic and lexical representations, which is automatically activated in the process of word recognition. This

facilitation is prospective, as it occurs upon presentation of the prime and persists until the target is presented. This automatic pre-activation by the prime does, however, dissipate rather quickly to reduce interference with subsequent word recognition (Forster & Davis, 1984).

The discovery of a lexical frequency attenuation effect in the long-term LDT led to the development of a *weak abstractionist model* of repetition priming (Scarborough, et al., 1977). *Lexical frequency* is a metric of how frequently a given word appears in a corpus of words, which serves as an approximation of participants' exposure to and use of words. Low-frequency words generally take longer to read and recognize due to less practice relative to high-frequency words (Forster & Davis, 1984). Because low-frequency words are encountered less frequently, they are more likely to produce a unique and salient episodic trace than high-frequency words (Forster & Davis, 1984). Repetition provides more facilitation for low-frequency targets than for high-frequency targets in long-term priming, as indexed by a larger reduction in button-press response times for low-frequency words (Scarborough, et al., 1977). In contrast, there is no frequency attenuation effect in short-term masked priming (which removes the episodic impact of the prime due to a lack of conscious recognition of it), nor in long-term LDTs in which the lexical decision is not made on the prime (i.e., no special emphasis for encoding) (Scarborough, et al., 1977; Forster & Davis, 1984). Due to the presence of frequency attenuation only in the long-term LDT with encoding emphasis on the prime, it follows that there is likely a long-term frequency-sensitive component of repetition priming (Forster & Davis, 1984). The frequency- and saliency-based modulation of repetition priming indicate that this long-term component comes from implicit or explicit retrieval of prime encoding from episodic memory. Weak abstractionist models overlap with pure abstractionist models such that the main effect of repetition is based on automatic activation of the lexical representation of the target by the prime,

leading to facilitated consecutive access. However, they diverge in the sense that episodic memory is a key additional component of long-term repetition priming (Scarborough, et al., 1977).

Pure Episodic Models

Tenpenny (1995) argued that weak abstractionist models are feasible, but that pure episodic models of repetition priming also cannot be disproven due to a general lack of understanding of human memory. *Pure episodic models* of repetition priming require that the orthographic codes from abstractionist models be reconceptualized as episodic representations of letters and words. These representations are encoded during prime presentation, then episodically retrieved to facilitate target processing.

Revised Automatic Prospective Model

Pure episodic models cannot explain how visually dissimilar exemplars of the same lexical entry at encoding and retrieval could produce priming; they implicitly rely on visual overlap of the prime and target. However, visually dissimilar versions of the same word (e.g., "DOG" and "dog") do reliably produce repetition priming effects (Bowers, 2000). Bowers (2000) argued that abstract orthographic codes (abstractionist) and episodic representations (memory-based) of letters/words are likely distinct and contribute differentially to the repetition priming effect. The existence of abstract orthographic codes for words, likely in the left hemisphere of the brain, would allow for visually dissimilar exemplars of words to map onto the same orthographic/lexical word representation (Bowers, 2000). Any exemplar of a given letter or word will map on to the same abstract orthographic code for that item, which facilitates both

word recognition and repetition priming (Bowers, 2000). According to this view, episodic representations of primes and targets also likely exist in certain contexts, such as in long-term priming when task emphasis leads to episodic encoding and retrieval (as evidenced by the frequency attenuation effect), but contribute minimally to the foundation of repetition priming. This more automatic account of repetition priming includes an assumption that episodic effects are completely eliminated in masked priming paradigms, and priming is fundamentally born of *automatic pre-activation* of the target's orthographic/lexical representation by the prime, making repetition priming a *prospective* process (i.e. the lexical entry does not need to be retroactively re-opened in immediate priming).

Retrospective Memory Recruitment Model

Findings about prime validity effects, as operationalized by lists with different proportions of repeated versus new trials, led to a bolstering of a *memory recruitment account* over the abstractionist accounts. Bodner and Masson (2001) argue that short-term masked priming restricts episodic processing because the prime is presented too briefly for explicit recognition, but it does not eliminate episodic involvement. They found significant repetition priming effects for masked non-words in an LDT when 80% of trials included a repetition (i.e., high prime validity). Additionally, significant non-word masked priming directly challenges the abstractionist idea that priming is based on facilitated activation of existing orthographic or lexical codes because those do not exist for non-words (Bodner & Masson, 2001). Rather, it implies that masked primes (in this case presented for merely 60ms) create an episodic trace which may be selectively recruited.

According to the memory recruitment account, primes do not automatically pre-activate target representations, they are recruited *retroactively* (i.e., following target presentation) based on 1) prime validity, 2) task difficulty, and 3) variation in target difficulty between trials (Bodner & Masson, 2001; Masson & Bodner, 2003). Prime information is recruited more often when it is more valid, as indicated by a higher-magnitude priming effect for words when the proportion of repeated trials is 80% than when it is 50% or 20%. It is worth noting that this prime validity effect only occurs when there is low variability in target difficulty (i.e., lexical frequency); the effect is eliminated because high target variability leads to a higher overall reliance on primes regardless of validity (Masson & Bodner, 2003). Additionally, lexical frequency interacts with masked repetition priming when prime validity is high, such that there is more priming for low-frequency words. Frequency interactions suggest *strategic* recruitment of primes based on task difficulty, were previously only found in long-term priming, and were used as support for the episodic account (Masson & Bodner, 2003; Scarborough, Cortese, & Scarborough, 1977). This recruitment account is built on evidence of context-sensitive memory recruitment, such as findings that study materials are recruited more when the test is more similar to study; primes are recruited more when there is more task-relevant overlap in the form of high RP (Bodner & Masson, 2004). Any masked or non-masked prime is episodically encoded regardless of awareness, and may be recruited later based on task conditions (Bodner & Masson, 2004). The prime processing operation is encoded and is likely to be retrieved in short-term priming due to the close temporal proximity of the target.

The priming facilitation provided by high RP is interpreted as a bias effect under recruitment accounts, similar to established episodic effects of word identification. The automatic spreading activation account might posit that orthographic/lexical code activation

increases when prime validity is high and is blocked when validity is low. However, abstractionist accounts would predict no cost on unrelated trials, and thus fails to explain why high validity improves performance on repetition trials by speeding responses and impairs performance on unrelated trials by increasing error rates (Masson & Bodner, 2003). According to the recruitment account, invalid trials suffer from interference of increased prime recruitment (Masson & Bodner, 2003; Bodner & Masson, 2004; Bodner, Masson, & Richard, 2006).

Summary of Repetition Priming Models

Overall, abstractionist models provide an automatic prospective account of repetition priming (Scarborough, et al., 1977; Forster & Davis, 1984; Tenpenny, 1995; Bowers, 2000). Abstract orthographic and lexical representations of the identity prime are activated during recognition, and this activation provides automatic prospective facilitation to target word processing given the close temporal presentation. Episodic models of repetition priming require that we reconceptualize those orthographic codes as episodic prime representations, which are retrieved during target processing (Tenpenny, 1995). These models were born from a body of long-term priming research, in which there is too much of a delay between prime and target presentation for any prospective pre-lexical prime activation to remain upon target processing. Revised abstractionist models have been developed, in which the core mechanism of immediate repetition priming facilitation is automatic and prospective (Bowers, 2000). There may also be episodic components to repetition priming under certain conditions, particularly with long delays (Bowers, 2000).

Distributional Analysis

As discussed, most repetition priming studies rely heavily on response times as a dependent measure. Thus, it is advantageous to study the full effects of experimental manipulations on reaction time distributions, which are almost always positively skewed (Balota & Yap, 2011). Balota and Yap (2011) surveyed 285 scientific articles published in prominent journals in 2010, and 49% of them included reaction time analysis; 95% of those relied primarily on the mean. It is possible that a substantial effect may be statistically insignificant based on the mean alone, due to opposing influences of skew and modal shifts. For example, if an experimental manipulation causes the distribution to be skewed to the right *and* the mode to be proportionally shifted to the left, the averaging of these differences may yield no significant difference in the means even though there is an effect of the manipulation. Thus, it is important to use more revealing methods of analysis, such as ex-Gaussian, which allows us to understand the influence of manipulations on response time distributions (Balota & Yap, 2011).

Ex-Gaussian analysis is a convolution of an exponential and a Gaussian distribution, which fits natural RT distributions well and allows us to examine how a variable both shifts and/or changes the shape of a distribution (Balota & Yap, 2011). There are three main parameters: mu, which is the mode of the Gaussian distribution, sigma, which is the standard deviation of the Gaussian distribution, and tau, which is the mean and standard deviation of the exponential distribution (Balota & Yap, 2011). Mu and tau sum to equal the mean, which facilitates implementation of this analysis in the means-dominated literature. A shift of only mu leads to a constant difference between conditions across the response time distributions, whereas a shift on tau leads to an increasing difference across the distribution (such that there is more difference between the slowest responses in each condition than between the fastest in each).

Effects on tau imply that there is some contingency to the priming facilitation, such that it is larger on slower, more effortful trials.

Effects on the different components of empirical ex-Gaussian distributions have different theoretical implications. The Gaussian component indexes responses based on automatic processes, given that automatic processes are intuitively normally distributed (Balota & Spieler, 1999). The exponential component, however, indexes processes which require more overt attention and strategy. Trials that require more attention, analysis, strategy, or consideration skew the distribution to the right with slower response times, and the experimental manipulations giving rise to them would have an effect mainly on tau (Balota & Spieler, 1999).

Ocular Response Time Measures

Nearly all of the aforementioned repetition priming research has relied upon manual button-press response times. Button-press response times provide some index of word processing time, but they also include time spent preparing and executing the response which confounds our primary dependent variable. A more precise and ecologically valid way to measure response times is by using contingent-display ocular response eye-tracking tasks, and quantifying response time as the time spent reading a word (Hoedemaker & Gordon, 2014; 2017). In contingent-display ocular-response tasks, participants see a series of equally spaced masks on the screen in place of words, and are instructed to move their eyes from left to right at a natural reading pace. Invisible boundaries are coded directly ahead of the x-coordinate of each word, which the movements of the eyes trigger to reveal the words as the eyes reach their position. The masks allow for an approximation of word processing time without the documented effects of parafoveal preview on reading times (Kornrumpf, Niefind, Sommer, & Dimigen, 2016).

Gaze duration is the variable most frequently used to operationalize reading time and is defined as the cumulative time, in milliseconds, a participant spends fixating on a word (Hoedemaker & Gordon, 2014; 2017). Gaze durations are more strongly negatively correlated with word frequency than manual responses, which reinforces their validity as a response time measure due to the well-documented effect of frequency on manual LDTs and traditional eye-tracking sentence reading times (Hoedemaker & Gordon, 2014; 2017). Additionally, eye movements in ocular tasks are highly congruent with naturalistic reading behavior, allowing for maintenance of task goals during response execution (i.e., a forward saccade to the next word) (Hoedemaker & Gordon, 2014; 2017). Given the validity of gaze durations in ocular tasks as a response time measure, as well as their temporal precision, using this method could lead to unique insight about the mechanisms of repetition priming and word recognition. For instance, distributional analysis of manual and ocular response times in lexical decision task experiments have led to divergent accounts of semantic priming (Hoedemaker & Gordon, 2014; 2017; Balota, Yap, Cortese, & Watson, 2008).

Distributional Analysis of Manual and Ocular Responses

Ex-Gaussian analysis has been performed on both ocular and manual response times to lexical decision studies of semantic priming (Hoedemaker & Gordon, 2014; 2017; Balota, Yap, Cortese, & Watson, 2008). The ocular response time results revealed a significant effect of semantic priming only on tau, which means that there is larger facilitation provided by semantic primes for target processing on slower trials (Hoedemaker & Gordon, 2017). The primes are recruited more heavily when the lexical decision is harder (i.e., takes longer to make), meaning that semantic priming has more of an effect when the task is more effortful. Hoedemaker and

Gordon (2014; 2017) interpreted these results within the compound-cue model of semantic priming, whereby the prime is retrospectively recruited after target detection due to the close temporal proximity of presentation. Due to their rapid sequential encoding in working memory, the pair serve as a compound cue for target retrieval (Hoedemaker & Gordon, 2017). The facilitation provided by the compound cues is greater for more effortful trials.

In contrast, ex-Gaussian analysis of button-press response times revealed an effect of semantic priming on mu but not tau (Balota, et al., 2008). Balota and colleagues (2008) interpreted these results in the context of a head-start account of semantic priming, whereby priming facilitates target processing equally regardless of target difficulty. This account is analogous to the automatic prospective accounts of repetition priming, but says that semantic primes pre-activate all potential target representations to facilitate processing. These differences in results have motivated the present study of repetition priming. Repetition priming is more simple than semantic priming and is a good place to start laying the foundation for mapping behavioral measures of prime facilitation to theoretical frameworks.

The Current Study

Due to the fact that most studies of priming use manual response times, the present study seeks to apply ex-Gaussian analysis to both manual and ocular response times in the same repetition-priming task. Ex-Gaussian analysis allows for a more fine-grained exploration of variable effect(s) across the response time distribution than means-based analysis (Balota & Yap, 2011). To our knowledge, there are no published studies that use ex-Gaussian analysis on manual repetition-priming response times. These experiments allow us to explore differences in results and interpretations based on the dependent response time measure, and contextualize the

results of the ocular task within the broader behavioral literature. Ocular response times are shorter and closer to word processing times than manual button-press response times (Hoedemaker & Gordon, 2014; 2017). Any discrepancy between the manual and ocular task results will be an important indication of the need to think critically about the dependent response time measure in word recognition studies, as well as the theoretical interpretations of results. Ocular and manual button-press response times have led to different theoretical accounts of the more complex phenomenon of semantic priming (Balota, et al., 2008; Hoedemaker & Gordon, 2014; 2017). Ocular response time measures are more ecologically valid, naturalistic responses, and can provide more fine-grained insight into priming mechanisms than manual response times can. The present study is composed of three animal-monitoring task experiments which manipulate short-term non-masked repetition priming. Experiment 1 uses ocular response times, and Experiments 2 and 3 use manual button-press response times.

EXPERIMENT 1

Introduction

Experiment 1 is a contingent-display ocular-response animal-monitoring task. In this experiment, participants are presented with five words on each trial and are asked at the end of each trial whether the name of an animal is present; this task ensures that participants access the meaning of the words. The contingent-display ocular-response method allows us to eliminate parafoveal preview and measure precise reading time, without the additional time it takes to press a button. This method is also closer to natural reading than button-press tasks, given that participants move their eyes forward to reveal the words at their own pace. Repetition is manipulated within the experiment, and gaze durations (response times) to primed and unprimed

words will be analyzed via ex-Gaussian analysis, allowing for isolation of the effects of repetition on changes of mode versus skew to the response time distributions. An effect on mu indicates a modal shift of the distribution as a result of manipulation, meaning that the prime provides roughly equivalent levels of facilitation to target processing across the distribution of response times. An effect on tau, on the other hand, indicates that the manipulation results in an increase in distributional skew; in other words, the prime provides more facilitation on trials with slower response times. I expect these gaze durations to be shorter and closer to word processing times than manual button-press response times (Hoedemaker & Gordon, 2014; 2017). I also expect to find an effect of repetition on mu and not tau, consistent with abstractionist accounts of repetition priming (Scarborough, et al., 1977; Forster & Davis, 1984; Tenpenny, 1995; Bowers, 2000; Balota, et al., 2008; Balota & Yap, 2011). I expect the processing facilitation provided by identity primes to be automatic and prospective because there is full orthographic and lexical overlap between the prime and target. However, given the findings of an effect of semantic priming on tau in gaze-contingent ocular-response tasks, it is possible we will find an effect of repetition on tau instead of, or in addition to, an effect on mu (Hoedemaker & Gordon, 2014; 2017).

Method

Participants

Forty-five undergraduate students at the University of North Carolina at Chapel Hill were recruited from the SONA participant pool to participate in the study for course credit. All participants were right-handed native English speakers. Seven participants were excluded from

the study due to an insufficient number of valid trials for ex-Gaussian analysis, leaving thirty-eight subjects.

Materials

There are 225 trials with five words in each trial. Stimuli consisted of various types of English words, excluding proper nouns. There are five practice trials, 160 experimental trials, and 60 filler trials in which one of the five words is the name of an animal (e.g. "horse"). Half of the experimental trials contain a repetition, and target words are counterbalanced such that they are preceded by the same word (identity prime) for half of the participants and by a control prime for the other half of the participants. All prime, target, and filler words are 4-6 letters long and low-frequency (log subtitle frequencies ranging from 0.48 to 1.23) (Balota et al, 2007). Control primes are precisely matched in length and frequency (to the hundredths place) with target words (except for four pairs, which were matched to the tenths place for frequency). Target words appear in positions 2-4 but never appear in the fifth position; repetition and control primes appear in positions 1-3. Trials are presented in a random order, except for the practice trials, which are the same for everyone.

Procedure

Participants completed a contingent-display animal monitoring task, in which they indicated via button-press at the end of each trial whether they saw the name of an animal. An example trial schematic can be seen in Figure 1. This task verifies that participants process the meaning of the words, ensuring full lexical access.

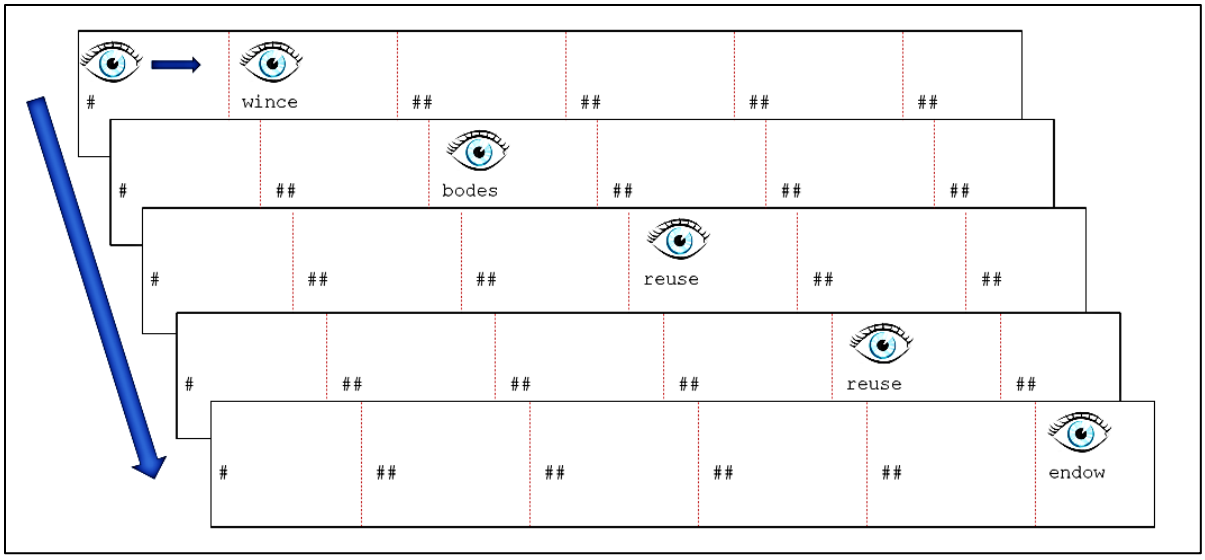

Figure 1. Example Trial Schematic. The red lines represent the invisible boundaries triggered by eye movements to each pair of octothorpes. This figure moves through time on the slanted y-axis, such that the top of the figure represents the beginning of the trial and the bottom represents the end. The eyes indicate approximate participate gaze.

Eye movements were recorded by an SR EyeLink 1000 from the participants' dominant eye, as determined by the "hole-in-the-hand" test (Roth, Lora, & Heilman, 2002). Participants sat in a well-lit room with their chin and forehead resting on a comfortable mount to minimize head movement. They were instructed to read the five words at a natural reading pace, and after reading all five words, press a button to indicate completion of the trial. At that point, a question appeared on the screen ("Animal?") to which participants responded by pressing one of two buttons on a game controller ("Yes" if there was an animal name in the trial, and "No" if there was not). Feedback was provided ("Correct" or "Incorrect"), and then the next trial began.

Following eye-tracking calibration, each experimental session began with five practice trials, which did not contain any of the words from the experimental lists. These practice trials

were excluded from all analyses. No words were repeated within a list (except intentional repetitions), and all experimental trials were presented in a random order within lists.

Each trial began with an octothorpe on the left side of the screen, and five masks (each consisting of two octothorpes) to the right. These octothorpe pairs were spaced equally across the screen horizontally, and marked the positions of the five words in each trial. Gaze-contingent invisible boundaries were coded before each word. Gaze contingencies were set so that each word was unmasked as the eyes entered its region from the left. Thus, the word appeared as participants fixated on its position, allowing for precise measurement of the start of processing. Once the eyes moved past the end boundary of each word, the word was re-masked and was no longer visible even if the participant moved their eyes back. This method was employed to prevent rereading and parafoveal preview, and to get a reliable metric for the time spend reading each word.

Analytic Approach

Response times to targets in critical trials were analyzed separately for primed and unprimed targets. Ex-Gaussian parameter estimates were obtained for every participant's target word response times separately in the primed and unprimed conditions using the QMPE v2.18 program for quantile maximum likelihood estimation (Cousineau, Brown, & Heathcote, 2004). Inferential statistics were run on the ex-Gaussian parameter estimates as dependent variables for each participant. Only accurate trials were be analyzed. Means-based and exploratory analyses were also conducted.

Results

There is a significant effect of repetition priming on mu ($t(37) = 6.20$, $p < .001$) and sigma ($t(37) = 2.40$, $p = .021$), but not tau ($t(37) = -0.73$, $p = .470$) (see Figure 2).

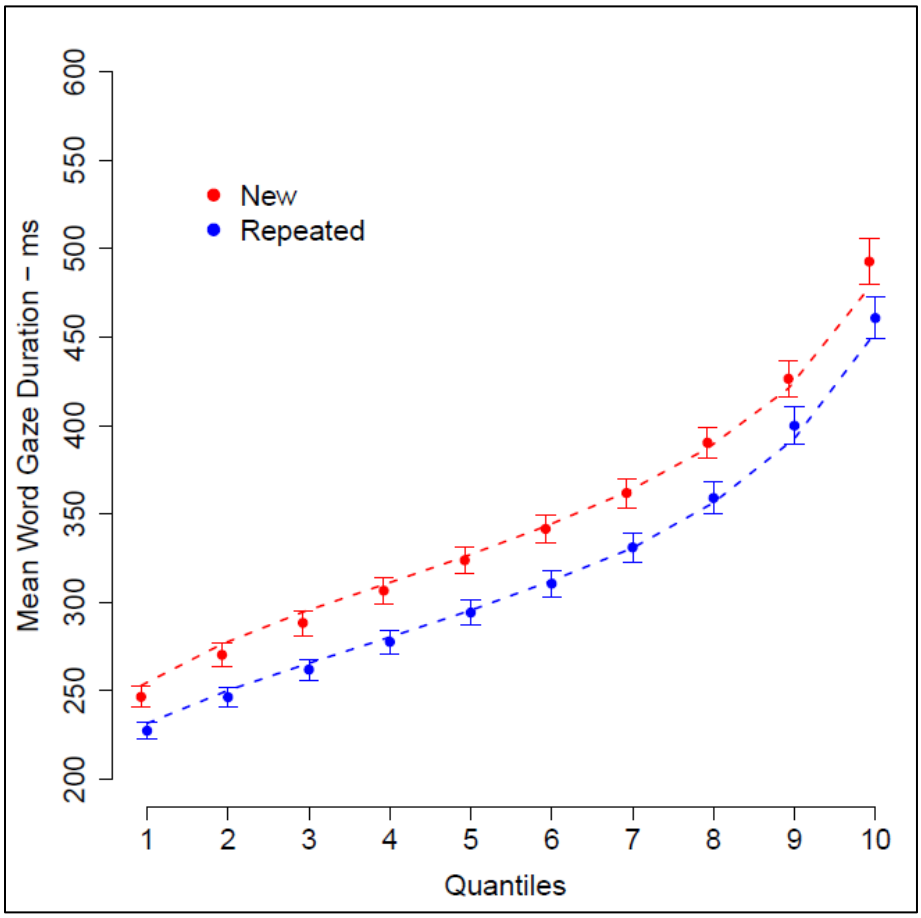

Figure 2. Mean Target Word Gaze Duration by Quantiles for Experiment 1. Dots represent the sample mean of the condition in each quantile, error bars indicate one standard error, and the dotted lines represent the fit of a simulation run with a 20,000-bootstrap sample. The mu effect can be seen in the relatively consistent distance between the two conditions in all quantiles. The sigma effect can be observed in the slight differences in error bars.

There was an effect of repetition on mean target response time ($t(37) = 8.22$, $p < .001$). We also performed a median split to divide the participants into groups of slower and faster responders; both groups still show an effect on mu (*faster:* $t(18) = 4.68$, $p < .001$; *slower:* $t(18) = 4.92$, $p < .001$) and on mean target response time (*faster:* $t(18) = 5.84$, $p < .001$; *slower:* $t(18) = 5.95$, $p < .001$), but not on tau (*faster:* $t(18) = 0.45$, $p = .661$; *slower:* $t(18) = 1.03$, $p = .318$).

Experiment 1 Discussion

The results of Experiment 1 indicate that the facilitation provided to target processing by identity primes is automatic and prospective (Nemeth & Gordon, 2020). Identity primes provide roughly equivalent facilitation across the response time distributions, as indicated by an effect on mu and not tau. These results are in line with abstractionist accounts of repetition priming (Scarborough, et al., 1977; Forster & Davis, 1984; Tenpenny, 1995; Bowers, 2000). These results contrast with the findings of Hoedemaker and Gordon (2014; 2017) that semantic primes have an effect on tau and not mu. Semantic priming is a more complex phenomenon than repetition priming because semantic-primes and targets are related, but usually do not overlap orthographically, and do not have full lexical overlap; repetition primes have full lexical and orthographic overlap with targets. The activation of these orthographic and lexical codes by the prime prospectively and automatically facilitate target processing. The median split results are evidence that this automatic and prospective effect is robust and present for the fastest and slowest responders. The additional effect on sigma merely indicates that there is more variability in response times to unprimed words than to repeated words.

EXPERIMENT 2

Introduction

The purpose of Experiment 2 is to extend the findings from Experiment 1 to a manual button-press task with as much methodological overlap with the ocular task as possible. By doing so, we will be able to compare the findings of the ocular task to those of a manual task, given the bulk of the behavioral repetition priming literature utilizes manual response times for analysis. Additionally, there are no published studies which use ex-Gaussian analysis to explore manual response times in a repetition-priming task. I expect to find an effect on mu and not tau, consistent with the results of Experiment 1 and with abstractionist accounts of repetition priming. However, ex-Gaussian analysis of manual and ocular response times have led to different theoretical interpretations of the facilitation provided by semantic primes; it is possible that a similar pattern will emerge for repetition priming (Balota, et al., 2008; Hoedemaker & Gordon, 2014; 2017). If we find an additional effect on tau, it will be clear that manual response times are sensitive to an additional, later, retrospective effect of repetition, as compared with ocular response times. If we find an effect only on tau, we will discover that manual response times are not sensitive to the early automatic facilitation provided by repetition primes, and are only sensitive to the later post-lexical facilitation. Such a finding would also substantiate the existence of multiple effects of repetition and indicate that the shorter manual response times are not sensitive to the later effect.

Method

Participants

Forty-seven native-English speakers were recruited to participate in this study; one participant was excluded from analysis due to having an insufficient number of valid trials for ex-Gaussian parameter estimates, leaving forty-six subjects. Participants were recruited from the University of North Carolina at Chapel Hill were recruited from the SONA psychology participant pool in exchange for course credit.

Materials

The materials in this experiment are identical to the materials in Experiment 1, with the only exception being that twenty-two of the non-animal words were replaced because they were similar to animal names (e.g., "catnap"). These words were replaced with words of the same length and log subtitle lexical frequency.

Procedure

This study was implemented online using the lab-js library, and hosted on Open Lab (Henninger, Shevchenko, Mertens, Kieslich, & Hilbig, 2020; Open Lab, 2020). The procedure is nearly identical to that of Experiment 1. Participants completed an animal monitoring task in which they responded, via keyboard button press, whether the name of an animal was present on each trial ('y' for yes, 'n' for no). At the beginning of the task, participants completed five practice trials to familiarize themselves with the task and environment. Feedback was provided only for incorrect responses, with a five-second on-screen message reading, "Incorrect." The

purpose of providing only negative feedback is to motivate participants to answer correctly, given that they participated at home instead of in the laboratory due to the COVID-19 pandemic.

Each trial began with an octothorpe on the left side of the screen, and five evenly spaced pairs of octothorpes (##) in a line to the right of the initial fixation. These octothorpe pairs are placeholders for the five words on each trial, and trials look the same way they did in Experiment 1 (see Figure 1). Instead of words being revealed in response to eye movements, participants pressed the space bar to begin the trial, at which point the first word will appeared. Participants were instructed to press the space bar to reveal a total of five words per trial at their own natural reading pace. Participants read the first word, pressed 'Space' to reveal the second and re-mask the first, and so on until they read all five words. At the end of each trial, a prompt ("Animal?") appeared on the screen, at which point the participants provided a yes/no keyboard response regarding the presence of an animal name on that trial ('y' for yes, 'n' for no). Feedback was provided if they answered incorrectly, and then the initial fixation screen for the next trial appeared.

Analytic Approach

The analytic approach to this experiment is identical to that of Experiment 1.

Results

There was a significant effect of repetition priming on tau ($t(45) = 3.14$, $p = .003$), but not on mu ($t(45) = 0.84$, $p = .407$) or sigma ($t(45) = 1.22$, $p = .230$) (see Figure 3).

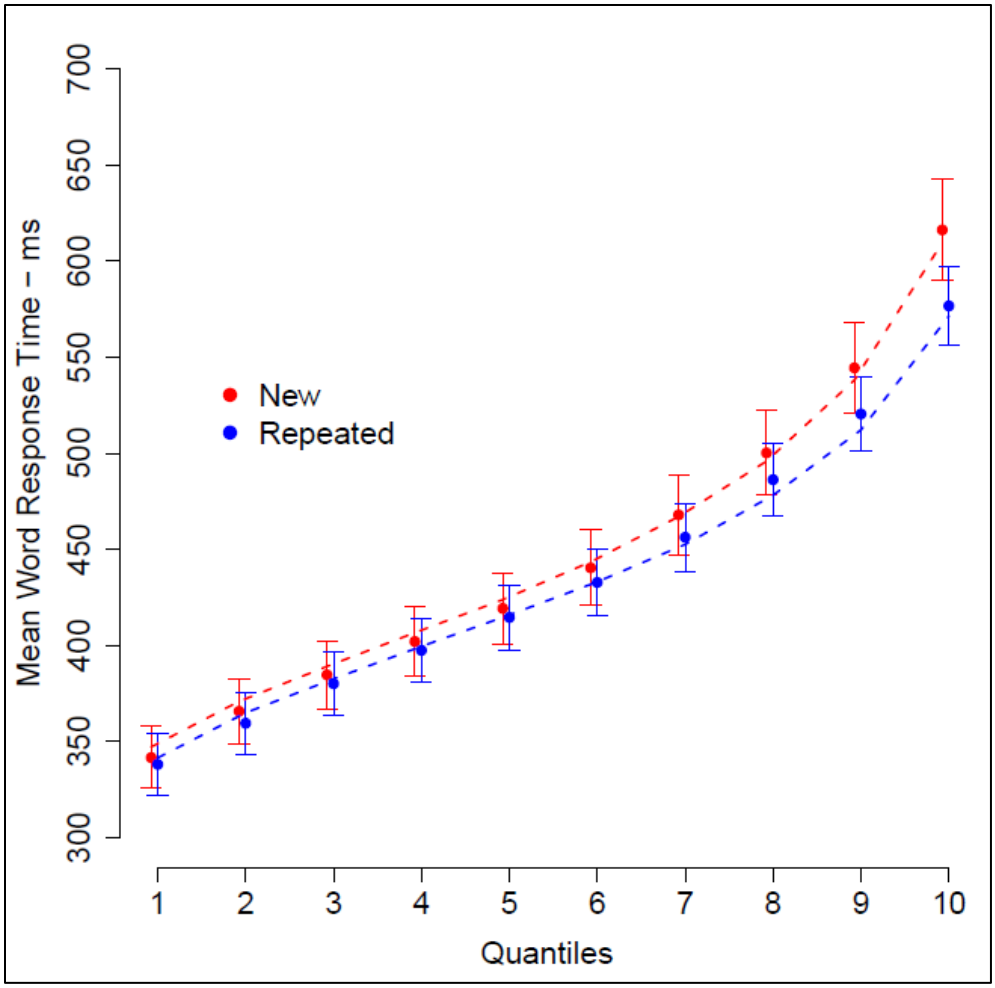

Figure 3. Mean Target Word Response Time by Quantiles for Experiment 2. Dots represent the sample mean in the given condition for each quantile; error bars represent one standard error; dotted lines represent the fit of a 20,000 bootstrap sample simulation. The effect of repetition on tau is seen as the larger difference between conditions in the slower quantiles.

The unexpected results of this experiment led to some exploratory analyses, in order to examine why we found an effect of repetition only on tau, then compare the results to those of Experiment 1. These discrepant findings suggest that ocular response times are sensitive to aspects of repetition priming that manual response times are not. We divided the participants into two groups: faster and slower responders, based on a median split of average response times,

in order to explore whether the lack of sensitivity to the early effect is due to the longer response times. It is possible that the faster responders also show an effect on mu.

The slower responders show an effect of repetition on tau ($t(22) = 3.92$, $p = .001$) but not on mu ($t(22) = 0.65$, $p = .521$). However, the faster responders do not show an effect of repetition on tau ($t(22) = 0.35$, $p = .731$) nor on mu ($t(22) = 0.52$, $p = .606$). Moreover, the faster responders did not show a main effect of repetition on mean target response times ($t(22) = 0.83$, $p = .417$), but the slower responders did ($t(22) = 6.13$, $p < .001$). The mean target response time effect is robust enough for the slower responders that it remains significant with all participants included ($t(45) = 4.57$, $p < .001$).

Experiment 2 Discussion

The results of this experiment indicated an effect of repetition on the ex-Gaussian parameter tau, but not on mu. These findings were unexpected and are not in line with the automatic head-start account of repetition priming, as was the case for Experiment 1. Furthermore, there was no evidence of any repetition effect for the faster responders in Experiment 2. The faster responders in Experiment 1 still showed a robust effect of repetition priming even though their average response times were far faster overall, so we must explore why there is no effect for the fast responders in the present study. Further, we must assess why those who do show an effect show it on tau and not mu. Absent the results of Experiment 1 and the lack of any repetition effect in the fast group, we may be tempted to simply interpret these effects under a memory-based account of priming, which highlights the importance of ocular response studies.

The main difference between Experiment 1 and Experiment 2 is the response measure. Thus, eliminating the role of eye movements would be helpful in understanding why we got this pattern of results. It is possible that the results of this study occurred because of some asynchrony between eye movements and button-press responses. In other words, it is possible that participants' eyes were not at the center of the words as they were revealed in this experiment; in Experiment 1, the eyes triggered invisible boundaries to reveal the words so we could be certain of synchrony between stimulus display and ocular fixation. It is also possible that participants fell into a pattern of responding rhythmically to the stimuli in this at-home online study, contributing to the absence of an effect in fast responders as well as to asynchrony between eye movements and button presses.

EXPERIMENT 3

Introduction

The unexpected tau effect, and lack of any repetition effect for faster responders, in Experiment 2 provided motivation for a follow-up experiment. We developed Experiment 3 using the same materials and animal-monitoring task from Experiment 2, but eliminated the role of eye movements and included a short, randomized display lag to eliminate any potential rhythmic response patterns. In this version of the experiment, the words are forwards-masked with a pair of octothorpes (like in Experiments 1 and 2), but the mask appears for a randomized duration of 150-350ms before the word is revealed. The purpose of the jittered masks is to eliminate any rhythmic or consistently-hasty response patterns that may have emerged in Experiment 2. All of the words are presented one at a time in the center of the screen in this experiment to eliminate the role of eye movements, and animal judgments are made on each

word individually. Due to the elimination of possible rhythmic responses and asynchrony between eye and stimulus positions, I expect to find some effect of repetition for all subjects in this experiment, unlike in Experiment 2. If we find any effect on mu, it will indicate that manual response times are sensitive to the automatic prospective facilitation detected by manual response times. If we find an effect on tau, we will interpret it as an additional retrospective effect of repetition which is not detected in ocular response times.

Method

Participants

Fifty-seven native-English speakers were recruited to participate in this study; seven participants were excluded from analysis due to having an insufficient number of valid trials for ex-Gaussian parameter estimates, leaving fifty subjects. Six more participants were excluded to equate the number of subjects in each counterbalanced list; the most recent participants were excluded. The total number of subjects included in the analysis for Experiment 3 is forty-four. Participants were recruited from the University of North Carolina at Chapel Hill from the SONA psychology participant pool in exchange for course credit.

Materials

The materials in this experiment are identical to the materials for Experiment 2.

Procedure

Like Experiment 2, this experiment was implemented online using the lab-js library, and hosted on Open Lab (Henninger, et al., 2020; Open Lab, 2020). Participants completed an

animal monitoring task in which they responded, via keyboard button press, whether each word was name of an animal was present on each trial (‘y’ for yes, ‘n’ for no).

Instead of presenting five words on each trial arranged horizontally and masked by octothorpes, as in the first two experiments, the five words in each trial were presented just one at a time in the center of the screen in Experiment 3. Before each word, a pair of octothorpes appeared at the center of the screen for a random jittered duration of 100-350ms before being replaced by the word. The order of the groups of five words per trial from Experiments 1 and 2 was preserved in this experiment, even though only one word appeared at a time. The order of the trials was again randomized for each participant. Participants judged, via button-press, whether each word was an animal, and received negative feedback (“Incorrect” message displayed for five seconds) for incorrect responses. At the beginning of the task, participants responded to the same five practice trial stimuli from Experiments 1 and 2, but these trials appeared to participants as twenty-five trials in this experiment due to each word being presented individually.

The inclusion of jittered masks guarantees that repeated words do not appear to be erroneously stuck on the screen, and also mitigates the risk of rhythmic responding. Presenting words in the center of the screen eliminates the role of eye movements present in Experiment 2, allowing us to make a more direct comparison to Experiment 1 in that regard.

Analytic Approach

The analytic approach to this experiment is identical to that of Experiments 1 and 2.

Results

There was a significant effect of repetition priming on tau ($t(43) = 5.24$, $p < .001$), but not on mu ($t(43) = 1.15$, $p = .256$) or sigma ($t(43) = 1.72$, $p = .093$) (see Figure 4).

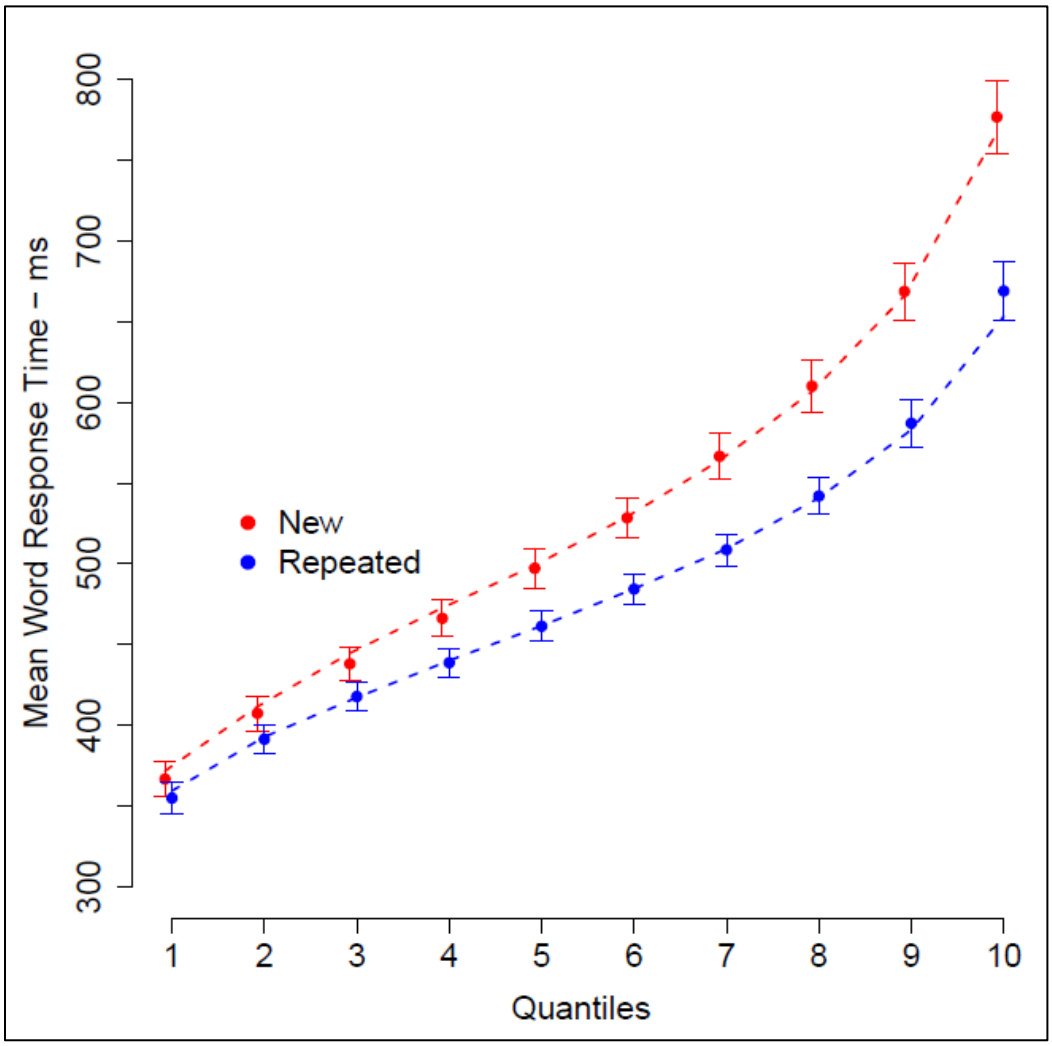

Figure 4. Mean Target Word Response Time by Quantiles for Experiment 3. Dots represent the sample mean in the given condition for each quantile; error bars represent one standard error; dotted lines represent the fit of a 20,000 bootstrap sample simulation. The effect of repetition on tau is seen as the larger difference between conditions in the slower quantiles.

Repetition has a significant effect on tau for the faster ($t(21) = 4.31$, $p < .001$) and slower ($t(21) = 3.25$, $p = .004$) responders in Experiment 3; neither group shows an effect on mu (*faster:* $t(21) = -0.58$, $p = .569$; *slower:* $t(21) = 2.06$, $p = .052$). Both groups also display an effect of repetition on overall mean response time (*faster:* $t(21) = 5.62$, $p < .001$; *slower:* $t(21) = 5.54$, $p < .001$; *overall*: $t(43) = 7.07$, $p < .001$).

Another thing to note is that the accuracy on animal trials is much lower in Experiment 3 (60%) than it was in Experiment 1 (91%) and Experiment 2 (91%). A one-way ANOVA reveals a significant difference in *false alarm rates* ($F(2,125) = 94.83$, $p < .001$), *hit rates* ($F(2,125) = 104.130$, $p < .001$), and d' ($F(2,125) = 123.041$, $p < .001$) between experiments. There are no significant differences between Experiments 1 and 2 with regard to *false alarm rate* ($t(82) = 0.75$, $p = .454$), *hit rate* ($t(82) = 0.15$, $p = .882$), or d' ($t(82) = -0.50$, $p = .620$). However, the *false alarm rate* is higher in Experiment 3 than Experiment 2 ($t(88) = -13.81$, $p < .001$) and Experiment 1 ($t(80) = -9.29$, $p < .001$); the *hit rate* is also lower in Experiment 3 than Experiment 2 ($t(88) = 11.27$, $p < .001$) and Experiment 1 ($t(80) = 11.05$, $p < .001$). The d' is also lower in Experiment 3 than Experiment 2 ($t(88) = 13.83$, $p < .001$) and Experiment 1 ($t(80) = 13.43$, $p < .001$). See Table 1 for a summary.

	Experiment 1	Experiment 2	Experiment 3
False Alarm Rate	0.019	0.014	0.097
Hit Rate	0.911	0.908	0.599
d′	3.757	3.840	1.620

Table 1. Animal Judgment Accuracy Table. False alarm rate is the proportion of trials on which participants said there was an animal when there was not one. Hit rate is the proportion of trials in which an animal was present and correctly identified by participants. D′ is a sensitivity measure of the distance between the signal and noise distributions; higher values represent higher sensitivity.

Experiment 3 Discussion

Experiment 3 revealed an effect of repetition on tau, indicating a systematic divergence of the response time distributions such that targets with slower responses benefitted more from priming than those with faster responses did. These results are in line with memory-based accounts of repetition priming; primes provide strategic and/or retrospective facilitation to target recognition (Scarborough, et al., 1977; Bodner & Masson, 2001; Masson & Bodner, 2003; Bodner & Masson, 2004). The memory-based literature states that the prime is episodically encoded and then retrieved upon target presentation to facilitate processing (Bodner & Masson, 2001). The degree of recruitment of these episodic traces is known to vary based on difficulty; targets with slower response times are more difficult to recognize than those with faster response times, and thus benefit more from the prime (Bodner & Masson, 2001; Balota & Yap, 2011). There is no evidence that specific target words are more difficult for all participants; all stimuli are low-frequency words and recognition difficulty varies between individuals.

Experiment 3 eliminated the potentially-confounding role of asynchronous eye movements that was present in Experiment 2 by presenting the words in the center of the screen. In this way, Experiment 3 is more directly comparable to Experiment 1. A random delay was also introduced in Experiment 3 to eliminate any potential rhythmic responding present in Experiment 2. The effect on tau and the overall mean reaction time effect were present in both faster and slower responders in this experiment, which was not the case in Experiment 2; this robust pattern increases confidence in the results of Experiment 3.

The differences in animal accuracy in this experiment are likely due to the fact that the proportion of animal trials is far lower, with responses given to each word rather than to groups of five words. Participants in this experiment had a higher false alarm rate, lower hit rate, and lower d′ as compared with the first two experiments, indicating that this task was more difficult for participants to perform accurately.

GENERAL DISCUSSION

In the present study, we conducted three repetition-priming animal-monitoring task experiments. Experiment 1 utilized contingent-display eye-tracking, and the dependent measure was gaze duration on repeated and unprimed target words. Experiments 2 and 3 utilized manual button-press response times. Experiments 1 and 2 both required participants to make an animal judgment after reading a series of five words per trial; Experiment 3 required an animal-judgment response on each word individually. Ocular response times reveal an effect of repetition on mu, and manual response times reveal an effect on tau. These results have led us to conclude that repetition provides both prospective (Experiment 1) and retrospective (Experiments 2 and 3) facilitation to target-word recognition. However, manual response times

are not sensitive to the early automatic effect. Figure 5 provides a visual summary of the results from all three experiments; it is clear that the response times in Experiment 1 are much faster overall than the manual response times in Experiments 2 and 3. It is also clear that the response times in Experiment 3 are much slower than the response times in Experiment 2 as a result of the methodological adjustments.

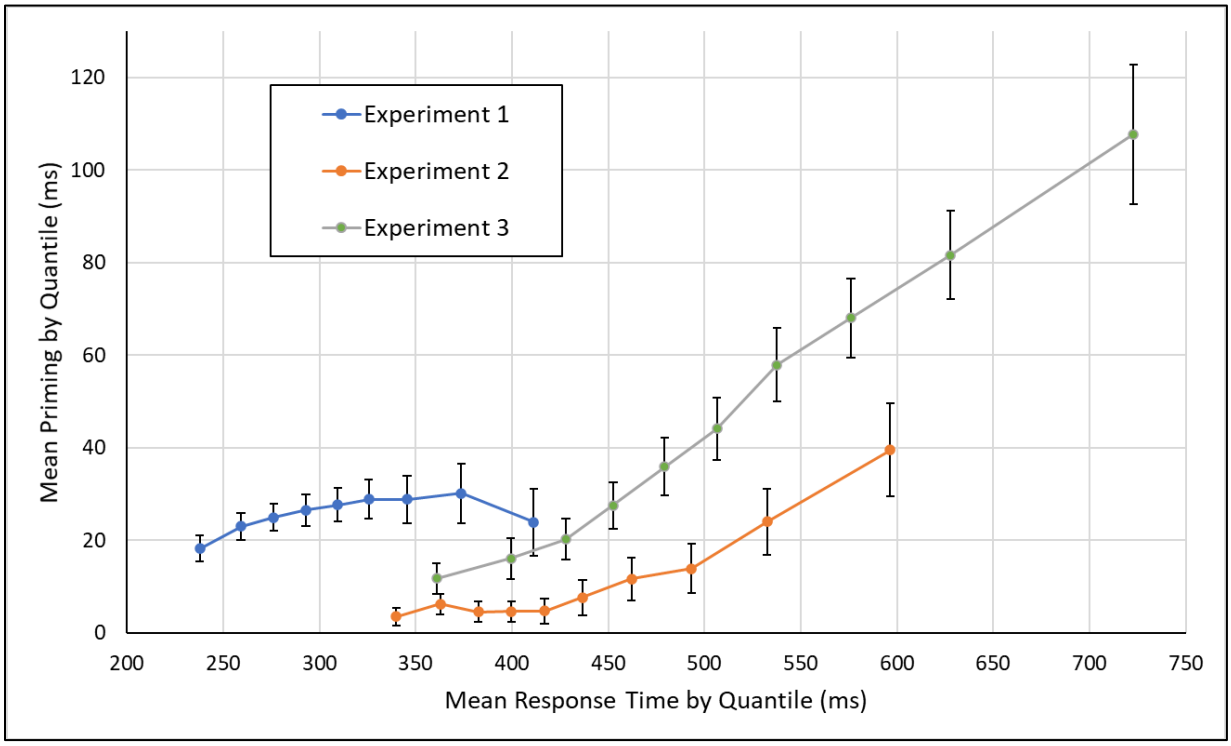

Figure 5. Mean Priming by Quantiles for Experiments 1-3. The y-axis designates the magnitude of priming in each quantile, calculated as the difference in response times to unprimed and repeated targets. The x-axis designates the mean response time in each quantile. Dots represent the sample mean for each quantile; error bars represent one standard error.

The results of Experiment 1 directly challenge memory recruitment accounts of repetition priming, and are in line with abstractionist accounts (i.e., repetition provides automatic

prospective facilitation) (Scarborough, et al., 1977; Forster & Davis, 1984; Tenpenny, 1995; Bowers, 2000; Balota & Yap, 2011). There is an effect of repetition only on mu, indicating roughly equivalent facilitation to the processing of all repeated words. This roughly equivalent effect size across the distribution indicates that the prime automatically and prospectively facilitates target recognition because the level of facilitation does not differ across trials. This equivalent facilitation can be seen in Figure 5, with the magnitude of the priming effect landing relatively consistently around 30ms across all ten quantiles. We can infer that trials with slower response times are more challenging than trials with faster response times. Therefore, according to the memory recruitment account, we would expect to have seen a tau effect, indicating more strategic facilitation on more difficult trials (Scarborough, et al., 1977; Bodner & Masson, 2001; Masson & Bodner, 2003; Bodner & Masson, 2004; Balota & Yap, 2011).

The results of Experiments 2 and 3 do indicate such an effect of repetition on tau (i.e., more facilitation on trials with slower response times). In Figure 5, we can see that the magnitude of the priming effect gets larger in the slower quantiles for Experiments 2 and 3. This effect on tau is detected by the slower manual responses yet is absent in the faster, more precise ocular response times; it is a later, post-lexical effect. The early, automatic, prospective effect detected in Experiment 1 is the most relevant to word recognition in a naturalistic-reading setting. When we read, we simply move our eyes from the left to the right at a normal pace; when a word is repeated immediately within a sentence, the orthographic and lexical representations activated by the prime provide automatic and prospective facilitation to processing it a second time. The response times in Experiment 1 are also far closer to natural reading times than those in Experiments 2 and 3 (see Figure 5) (Hoedemaker & Gordon, 2014; 2017).

All three of the present experiments employ non-masked short-term priming in a naturalistic, self-paced reading task, making them quite distinct from the bulk of the behavioral priming literature. During non-masked self-paced word recognition, full orthographic and lexical activation of the prime is achieved before reading the target. This activation provides equivalent, automatic, prospective facilitation to target recognition regardless of item difficulty, according to analysis of ocular response times. There is also a later, strategic or retrospective component of repetition priming facilitation, and this post-lexical effect is detected in manual response times. In Experiment 1, the words were revealed as participants' eyes reached them; in Experiments 2 and 3, the words were revealed when participants pressed a button to reveal them. It is possible that this additional delay or asynchrony led to a dampening of the orthographic activation by the prime by the time the target was revealed, eliminating the detection of automatic prospective effects in manual response time distributions (see Figure 5). In Experiment 2, there is no way to be certain whether participants' eyes were focused on the word as it was revealed; it is possible that participants indiscriminately pressed the space bar quickly and gradually swept their eyes from left to right, relying on parafoveal information for word processing. The absence of any repetition effect for the faster half of responders supports this possibility. Participants only needed to make one animal judgment per five-word sequence in Experiments 1 and 2, which allows for a consolidation of effort to detect animal names and thereby faster response times. In Experiment 3, which had slower response times than Experiment 2, we can be more confident of synchrony between eye and stimulus position due to the central location of all stimuli (see Figure 5). We can also be more confident that participants were not just responding as fast as possible before fully processing the words due to the inclusion of the randomized display lag, and to the fact that an animal judgment response was required for

every word in Experiment 3. However, it is possible that the orthographic and lexical activation of the prime dissipated before the target words appeared in Experiment 3. The delay between the prime response and target display ranged from 150 to 350ms; many target response times in Experiments 1 and 2 fall within this range (see Figure 5). By the time a target appeared after a forwards-mask in Experiment 3, it may have already been recognized and responded to in Experiments 1 or 2 (see Figure 5). Thus, the added delay in Experiment 3 may have eliminated the automatic and prospective facilitation of the prime to the target due to a dissipation of orthographic activation during mask display. The asynchrony between eye position and stimulus display may have eliminated the detection of an early automatic effect in Experiment 2. It is also possible that the automatic prospective facilitation was present in Experiments 2 and 3, but was not detected in the manual response times because they are so much slower than ocular response times. In Figure 5, we can see that the majority of the responses (i.e., the first seven quantiles) to targets in Experiment 1 are faster than the responses in the very first quantile in either of the subsequent experiments.

The present study illustrates that there are both early automatic and later episodic components of non-masked immediate repetition priming. Experiment 1 utilized ocular response times, which are shorter, more highly correlated with lexical frequency, and less confounded with post-lexical processes than button-press response times are (Hoedemaker & Gordon 2014; 2017). Moving the eyes to the right is a far more naturalistic and instinctive response during reading than pressing buttons is; the only task the participant has is to process the word and naturally move the eyes forward. In button-press experiments, the participant must execute a manual button-press response which is not natural during reading, thereby changing the task demand and slowing the response time distributions. Manual response times are sensitive to a

different, later, post-lexical effect than ocular response times are, and this effect is potentially amplified by the added task of pressing a button. Absent the ocular data (Experiment 1), this post-lexical effect (Experiments 2 and 3) would unconditionally support retrospective theories of repetition priming. The lack of sensitivity to the early automatic effect in manual response times to overtly-primed targets raises concern about the use of manual response times as the sole or primary dependent measure in priming and word recognition studies (Bodner & Masson, 2001; Hoedemaker & Gordon, 2014; 2017; Nemeth & Gordon, 2020). Ex-Gaussian analyses of manual and ocular lexical decision time data support different theoretical accounts of semantic priming as well (Balota, Yap, Cortese, & Watson, 2008; Hoedemaker & Gordon, 2014; 2017). Given the different repetition effects captured by different behavioral response time measures, future eye-tracking research is needed to develop a more robust theoretical account of priming facilitation.

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